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Implementation of an Ultrasonic Distance Measuring System with Kalman Filtering in Wireless Sensor Networks for Transport Logistics

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Abstract

In this paper an empirical study about distance measurements with ultrasonic sensors within an intermodal container is presented. In a previous work [1] the Received Signal Strength Indicator (RSSI) was used for measuring the distance between two nodes in a Wireless Sensor Network (WSN). Since RSSI revealed a huge distance measurement error (52 cm) and standard deviation (47 cm) a Time-of-Flight (ToF) approach is applied. For this purpose self-developed ultrasonic sensor boards are equipped on the sensor nodes and a Time-Difference-of-Arrival (TDoA) algorithm is implemented. Afterwards, the system is tested and calibrated to decrease the distance error. Then a multi stage filter, including Kalman filtering [2], is implemented to enhance the measurement stability. The following tests in the container reach a measuring accuracy around 1.5 cm with a standard deviation of 0.4 cm under the same environmental conditions.

Keyword: Wireless Sensor Networks; Distance Measurement; Ultrasonic; Kalman Filter; Logistic applications

1. Introduction

The online monitoring of the environmental condition in containers becomes very important for modern transport logistics. Due to low energy consumption and high flexibility wireless sensor networks offer a promising solution for this task [3]. The localization of the sensor nodes in a WSN enables the assignment of sensor values to their measuring points, and therefore e.g. to generate a temperature map of a building [4]. But there are many other applications for distance measurement such as security (open door/cargo securing) or content level monitoring.

In order to achieve a precise distance measurement the Time-of-Flight approach TDoA is applied, because previous distance measurements based on RSSI produced only poor accuracy and stability. To enhance the

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information value of the system a multi stage filter is implemented, which includes Kalman filtering and considers the hardware boundaries of the system as well as the maximum speed of the object.

2. Distance Measurement Technique

Measuring the distance to an object can be done in several ways according to the requirements of the application [5]. Apparently, we need a contact less technique in our WSN with low complexity but nevertheless accuracy. Since RSSI couldn't satisfy our demand for reliability we decided to use a Time-of-Flight based technique.

The Time-Difference-of-Arrival (TDoA) approach takes advantage of the unequal propagation speed of two signals. Knowing both speeds (v_{RF}, v_{US}) and the time difference of arrival Δt the distance d can be calculated (Fig. 1). For TDoA two signals with different propagation speed, and therefore two types of transceivers, are needed. In this work wireless sensor nodes (TmoteSky [6]) with self-developed ultrasonic sensor boards (Fig. 2) are used. The software implementation of the sensor board driver as well as the TDoA protocol has been done using TinyOS [7].

3. Filtering and Calibration

Since the first measurements in an office showed some outliers exceeding the range of physically possible values, a filter has to be implemented. In the first stage the hardware limits of the system have been determined empirically, which is equal to the working range of the system. Due to the limited speed of the microcontroller the consecutive receiving of the two signals can't be detected faultless, if the time difference of arrival is too small. Therefore, we introduce d_{min} = 45 cm as the minimum measurable distance. The second limit is caused by the damping of the ultrasonic signal and defines the maximum distance d_{max} = 650 cm.

In the next step the maximum movement depending on the sampling rate and the maximum speed of the device is taken into account. In our application the maximum speed of a forklift truck (20 km/h) will be used and the sample rate is set to 5 Hz. This results in the maximum displacement limit Δd_{max} = 5.6 m/s · 0.2 s = 1.12 m.

After setting up the hardware limits we observed an offset and linear error of the distance measurements. Therefore, a calibration formula is obtained by comparing the measured data to the desired values. For this task we took 3000 samples at three different distances and calculated the regression line using MATLAB (Fig. 3).

Finally, the Kalman filter [8] is integrated in the multi stage filter according to the program flow chart shown in Fig. 4. First, the hardware limits (d_{min}, d_{max} and Δd_{max}) described above will be considered in an if-clause. Then the constants process noise covariance Q and measurement noise covariance R will be defined, if the filter has not already been initialized. In this case the initial values for the a posteriori estimate error covariance P and the a posteriori state estimate $\hat{x}$ have to be set, too. For all other cases (following measurements) the a priori estimate $\hat{x}^-$ and the a priori estimate error covariance P^- will be calculated using the time update equations. In the same way $\hat{x}$, P and the gain K are computed via the measurement update equations. In all cases the old data d_{old} has to be overwritten by the new data d_{new} to enable the calculation of future displacements.

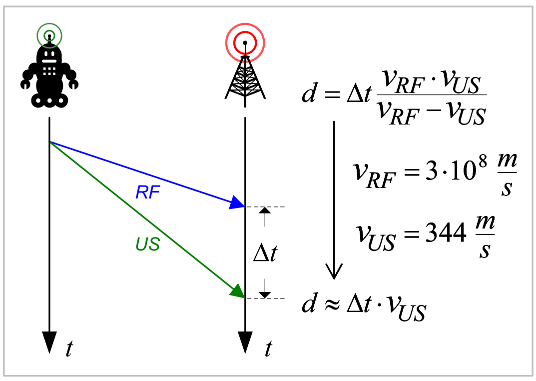

Fig. 1: TDoA Approach for Distance Measurement

Fig. 2: Wireless Sensor Node with Ultrasonic Sensor Board

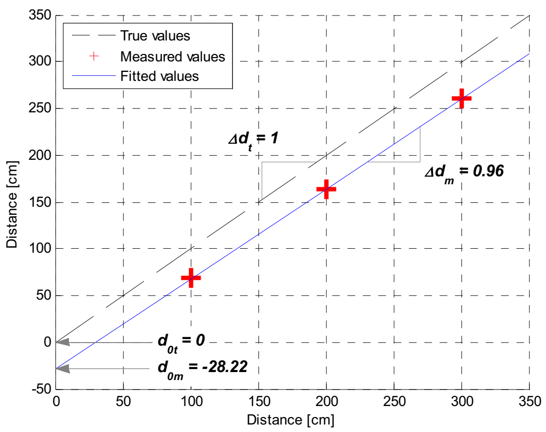

Fig. 3: Regression Line of Distance Measurements for Calibration

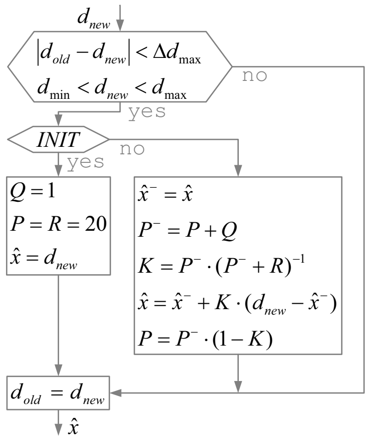

Fig. 4: Pseudo Code of the Kalman-Filter

4. Experimental Setup

After implementing the filter stages and calibrating, the practical measurements are carried out in a closed Twenty-Foot Equivalent Unit (TEU) container. The placement of the wireless sensor nodes is shown in Fig. 5, where index 1 to 6 denotes the different positions of the US-Receiver. One thousand samples are taken into account for each of the six distance measurements and sent wirelessly to the base station. To avoid packet loss the base station is also placed in the container and connected to a laptop via a USB cable. The raw data, without Kalman filter, will be sent simultaneously to enable the direct comparison of the data.

5. Results

The mean value and standard deviation of the measuring data with and without Kalman filter are compared in Tab. 1. As expected the mean values (μ_{raw}, μ_{kalman}) for each distance of both implementations are virtually identical, while the standard deviation (σ_{raw}, σ_{kalman}) has been reduced by the Kalman filter. This can also be seen in Fig. 6, where the measurement of 3 m is illustrated in detail as an example. Obviously, the filtered data has a much smoother curve and smaller range than the raw data. The local dependency of the standard deviation can be seen in Fig. 7. Due to greater multipath interference near a wall the standard deviation has a bathtub curve characteristic. This effect is also minimized by the filter stages.

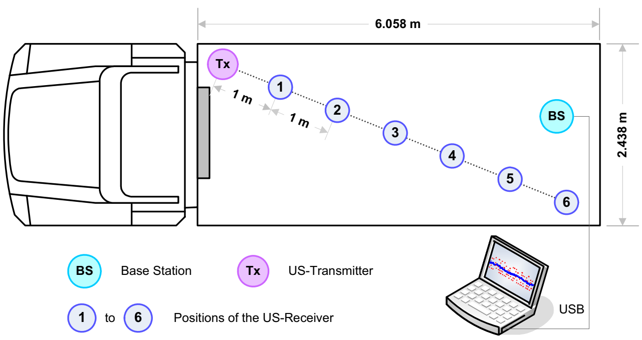

Fig. 5: Experimental Setup

Table 1: Results of the Distance Measurements [cm].

True Values	Measured Values		Kalman Filter	
	μ_{raw}	σ_{raw}	μ_{kalman}	σ_{kalman}
100	100.30	2.43	100.29	0.59
200	201.64	1.83	201.63	0.35
300	301.09	1.85	301.08	0.34
400	402.34	1.78	402.33	0.33
500	501.30	1.88	501.29	0.37
600	602.20	2.48	602.20	0.64

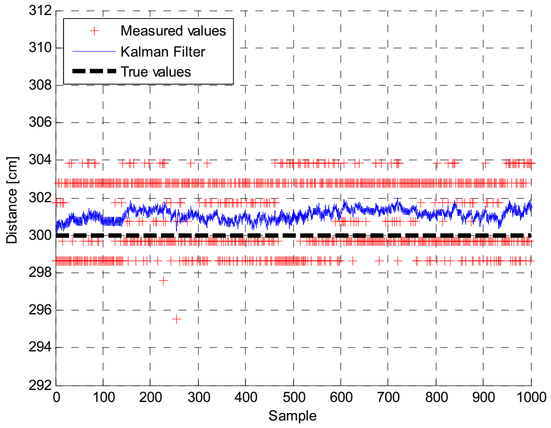

Fig. 6: Comparison of Distance Values for 3 m (Measured vs Kalman)

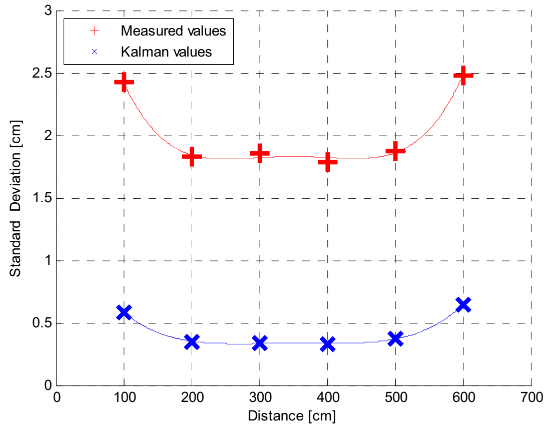

Fig.7: Comparison of the Standard Deviation of Distance Values (Measured vs Kalman)

6. Conclusion and Future Work

The practical experimental results show that with the TDoA approach a high accuracy of 1.5 cm is achieved. In addition the standard deviation could be reduced by the factor 4.5 from 2 cm to 0.44 cm. The use of the multi stage filter enhanced the reliability, which makes the distance measurement more efficient.

Future work will focus on automatic calibration of the system, to cancel out the influence of temperature and humidity. Another task is to analyze the applicability of dynamic measurements (moving objects) and the integratability in a multilateration system for localization.

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References

[1] Wang X, Bischoff O, Laur R, Paul S. *Localization in Wireless Ad-hoc Sensor Networks using Multilateration with RSSI for Logistic Applications*. Proceedings of Eurosensors Conference; 2009, p. 461–464.

[2] Kalman RE. *A New Approach to Linear Filtering and Prediction Problems*. Transaction of the ASME-Journal of Basic Engineering; 1960, p. 35–45.

[3] Jedermann R, Behrens C, Westphal D, Lang W. *Applying autonomous sensor systems in logistics – Combining sensor networks, RFIDs and software agents*. Sensors and Actuators A 2006;132:370–375.

[4] Watts W, Koplow M, Redfern A, Wright P. *Application of Multizone HVAC Control Using Wireless Sensor Networks and Actuating Vent Registers*. Energy Systems Laboratory, 2007.

[5] Joeckel R, Stober M, Huep W. *Elektronische Entfernungs- und Richtungsmessung und ihre Integration in aktuelle Positionierungsverfahren*. Heidelberg:Wichmann; 2007.

[6] TmotSky Brochure, Datasheet and Quick Start Guide from http://www.sentilla.com/moteiv-transition.html.

[7] TinyOS Homepage http://www.tinyos.net/.

[8] Bishop G, Welch G. *An Introduction to the Kalman Filter*. Working Paper, Department of Computer Science, University of North Carolina at Chapel Hill., 2003.